Controller Design of a New Quadrotor Manipulation System Based on Robust Internal-loop Compensator

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***Abstract*—This paper introduces control design of an aerial manipulator which consists of 2-link manipulator attached to the bottom of a quadrotor. This new system presents a solution for the limitations found in the current quadrotor manipulation system.The proposed robot enables the end effector to achieve any arbitrary position and orientation, and thus it increases its degrees of freedom from 4 to 6. Also, it provides enough distance between the quadrotor and the object to be manipulated. To study the feasibility of the proposed system, a quadrotor with high enough payload to add the 2-link manipulator is designed and constructed. The system parameters are identified to be used in the simulation and controller design of the proposed system. System modeling are described briefly. The controller of the proposed system is designed based on Robust Internal-loop Compensator (RIC) and compared to Fuzzy Model Reference Learning Control (FMRLC) technique which was previously designed and tested for the proposed system. These controllers are tested in order to achieve system stability and trajectory tracking under the effect of picking/placing a payload as well as under the effect of changing the operating region. Simulation framework is implemented in MATLAB/SIMULINK environment. Simulation results verifies the effectiveness of the proposed control technique.**

I. Introduction

Quadrotor is one of the Unmanned Aerial Vehicles (UAVs) which offer possibilities of speed and access to regions that are otherwise inaccessible to ground robotic vehicles. Quadrotor vehicles possess certain essential characteristics, such as small size and cost, Vertical Take Off and Landing (VTOL), performing slow precise movements, and impressive maneuverability, which highlight their potential for use in vital applications. Such applications include; homeland security (e.g. Border patrol and surveillance), military surveillance, and earth sciences (to study climate change, glacier dynamics, and volcanic activity) [1]–[4]. However, most research on UAVs has typically been limited to monitoring and surveillance applications where the objectives are limited to ”look” and ”search” but ”do not touch”. Due to their superior mobility, much interest is given to utilize them for mobile manipulation such as inspection of hard-to-reach structures or transportation in remote areas. Previous research on aerial manipulation can be divided into three categories. The first approach is to install a gripper at the bottom of an UAV to hold a payload.In [5]–[7], a quadrotor with a gripper is used for transporting blocks and to build structures. The second approach is to suspend a payload with cables. In [8], an adaptive controller is presented to avoid swing excitation of a payload. In [9], specific attitude and position of a payload is achieved using cables connected to three quadrotors. The other types of research are concerned about interaction with existing structures, as example, for contact inspection. In [10] research has been conducted on utilizing a brush as a manipulator. However, the above approaches have limitations for manipulation.

For the first category using a gripper, payloads are rigidly connected to the body of an UAV. Accordingly, not only the attitude of the payload is restricted to the attitude of the UAV, but also the accessible range of the end effector is confined because of the UAV body and blades. In the second type using cables, the movement of the payload cannot be always regulated directly because manipulation is achieved using a cable which cannot always drive the motion of the payload as desired. The last cases are applicable to specialized missions such as wall inspection or applying normal force to a surface.

To overcome these limitations, one alternative approach is to equip an aerial vehicle with a robotic manipulator that can actively interact with the environment. For example, in [11], a test bed including four-DOF robot arms and a crane emulating an aerial robot is proposed. By combining the mobility of the aerial vehicle with the versatility of a robotic manipulator, the utility of mobile manipulation can be maximized. When employing the robotic manipulator, the dynamics of the robotic manipulator is highly coupled with of the aerial vehicle, which should be carefully considered in the controller design for the aerial vehicle. Also, an aerial robot needs to tolerate the reaction forces from the interactions with the object or external environment. These reaction forces may affect the stability of an aerial vehicle significantly.

In [12], we propose a new aerial manipulation system that consists of a 2-link manipulator attached to the bottom of a quadrotor. This new system presents a solution for the limitations found in the current quadrotor manipulation systems. First, our proposed aerial manipulator has the capability of manipulating the objects with arbitrary location and orientation (DOF are increased from 4 to 6). Second, the manipulator provides sufficient distance between quadrotor and object location. Third, it is based on the minimum manipulator weight for aerial manipulation. Moreover, a controller is designed based on feedback linearization to track desired trajectories. Controlling the movements in the horizontal directions is simplified by utilizing the derived nonholonmic constraints. In [13], The dynamic model of this system is derived taking into account the effect of adding a payload to the manipulator, in addition to, the design of two controllers namely, Direct Fuzzy Logic controller and Fuzzy Model Reference Learning Control applied to this system, are presented.The simulation results indicate the outstanding performance of the FMRLC and the feasibility of the proposed robot. In [15], an aerial manipulation using a quadrotor with a 2 DOF robotic arm is presented but with different configuration from us. It did not provide a solution for the limited DOFs problem of aerial manipulation.

This proposed system opens new application area for robotics. Such applications are inspection, maintenance, firefighting, service robot in crowded cities to deliver light stuff such as post mails or quick meals, rescue operation, surveillance, demining, performing tasks in dangerous places, or transportation in remote places.

In this paper, brief description, methodology to identify system parameters, dynamics, and control design based on Robust Internal-loop Compensator (RIC), comparison study between RIC- and FMRLC-based control design of the proposed quadrotor manipulation system, are presented.

This paper is organized as follows. Description of the proposed system is described in section II. Section III introduces the system dynamic analysis as well as identified system parameters. The proposed control system is presented in section IV. In section V, simulation results using MATLAB/SIMULINK are presented. Finally, the main contributions are concluded in section VI.

II. Description of the Proposed System

The structure of the proposed system is shown in Fig. 1 using a 3D CAD model. The proposed quadrotor manipulation system consists mainly from two parts; the quadrotor and the manipulator. During the reset of this section, the design of each of them is presented such that they can combined, and then, perform the required task.

A. The Two-Link Manipulator

The design of this manipulator is based on light weight and enough workspace under the quadrotor. Our target is to design a light and simple 2 DOF manipulator that can carry as much as possible of a payload. One of the available and famous company to sell the components of such type of manipulator is "LYNXMOTION" [16].

The arm components are selected, purchased and assembled such that the total weight of arm is 200 g and can carry a payload of 200 g [17]. The arm components are:

- Three servo motors: HS-422 for gripper, HS-5485HB for joint 1, and HS-422 for joint 2.

Fig. 1. 3D CAD Model of the New Quadrotor Manipulation System

- Serial servo controller (SSC-32): Interface between the main control unit and the servo motors.
- Arduino board (Mega 2560): Implement manipulator control algorithm.
- PS2 R/C: Remote controller to send commands to manipulator.
- Motor accessories: Aluminum Tubing - 1.50 in, Aluminum Multi-Purpose Servo Bracket Two Pack, Aluminum Tubing Connector Hub, and Aluminum Long "C" Servo Bracket with Ball Bearings Two Pack.

B. Quadrotor

The quadrotor components are selected, purchased and assembled such that it can carry payload = 500 g (larger than the total arm weight including the maximum payload value). The quadrotor components are:

- Airframe: Mechanical structure of an aircraft that supports all the components, "ST450 metal folding".
- Rotor Assembly: Propeller (EPP1045), Electric Motor (930KV ST2812), and the Electronic Speed Controller (Lulin 30 A). It can produce approximately 400 g of thrust force.
- Microcontroller Unit: Implementation of stabilization control algorithms, Arduino Mega 2560.
- Wireless Communication: Two XBee modules are going to be used: one for the quadrotor and another in the ground station computer that will handle all telemetry for system identification and control purposes, Zigbee Pro-63 mW PCB Antenna Series2 .
- Sensors: Providing information like aircraft attitude, acceleration, altitude, global position. Inertial Measurement Unit (10 DOF Multiwii ZMR), Sonar unit (SRF04), and GPS unit (SKM53).
- Battery: Lithium Polymer Battery is used to power both the electronics components and the motors.

III. Dynamic Analysis and Identification

The manipulator has two revolute joints. The axis of the first revolute joint (z_0), that is fixed with respect to the quadrotor,

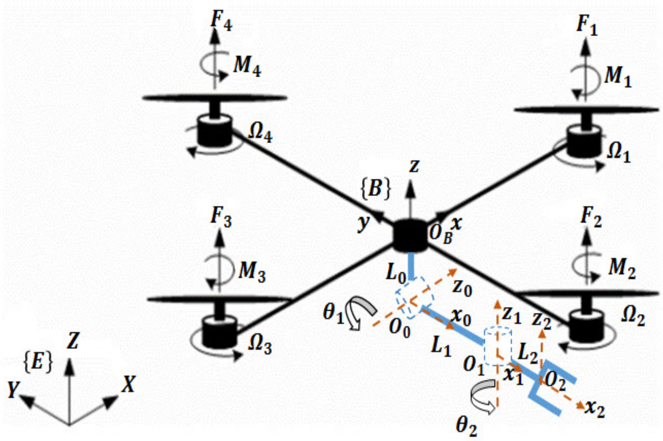

Fig. 2. Schematic of Quadrotor Manipulation System Frames

is parallel to the body x-axis of the quadrotor (see Fig. 2). The axis of the second joint (z_1) will be parallel to the body y-axis of quadrotor at home (extended) configuration. Thus, the pitching and rolling rotation of the end effector is now possible independently on the horizontal motion of the quadrotor. Hence, with this new system, the capability of manipulating objects with arbitrary location and orientation is achieved because the DOF are increased from 4 to 6.

Derivation of the equations of motion for the quadrotor manipulation system is presented in details in [12].

Fig. 2 presents a sketch of the quadrotor-manipulator system with the relevant frames. The orientation of the quadrotor is represented through Euler Angles. A rigid body is completely described by its position and orientation with respect to a reference frame {E}, O_I-$X\ Y\ Z$, that is earth-fixed. Let

$$R_I^B = \begin{bmatrix} C(\psi)C(\theta) & S(\psi)C(\theta) & -S(\theta) \\ -S(\psi)C(\phi) + S(\psi)S(\theta)C(\psi) & C(\psi)C(\phi) + S(\psi)S(\theta)S(\phi) & C(\theta)S(\phi) \\ S(\psi)S(\phi) + C(\psi)S(\theta)C(\phi) & -C(\psi)S(\phi) + S(\psi)S(\theta)C(\phi) & C(\theta)C(\phi) \end{bmatrix} \tag{1}$$

be the rotation matrix expressing the transformation from the inertial frame to the body-fixed frame{B}, O_B-x y z, where ϕ, θ, and ψ are Euler angles. Note that $C(.)$ and $S(.)$ in (1) are short notations for $cos(.)$ and $sin(.)$. Let us assume a small angles of ϕ and θ, then the corresponding time derivatives of Euler angles are equal to the body-fixed angular velocity components.

In Fig. 2 the frames satisfy the Denavit-Hartenberg convention [18]. The position and orientation of the end effector relative to the body-fixed frame is easily obtained by multiplying appropriate homogeneous transformation matrices [12], [18].

A. System Dynamics

Applying Newton Euler algorithm [19] to the manipulator considering that the link (with length L_0) that is fixed to the quadrotor is the base link, one can get the equations of motion of the manipulator as well as the interaction forces and moments between the manipulator and the quadrotor. The effect of adding a payload to the manipulator will appear in the parameters of its end link, link 2, (e.g. mass, center of gravity, and inertia matrix). Therefore, the payload will change the overall system dynamics.

The equations of motion of the manipulator are:

$$M_1\ddot{\theta}_1 = T_{m_1} + N_1 \tag{2}$$

$$M_2\ddot{\theta}_2 = T_{m_2} + N_2 \tag{3}$$

where, T_{m_1} and T_{m_2} are the manipulator actuators' torques. M_1, M_2, N_1, and N_2 are nonlinear terms and they are functions in the system states as described in [12].

The Newton Euler method are used to find the equations of motion of the quadrotor after adding the forces/moments applied by the manipulator are:

$$m\ddot{X} = T(C(\psi)S(\theta)C(\phi) + S(\psi)S(\phi)) + F^I_{m,q_x} \tag{4}$$

$$m\ddot{Y} = T(S(\psi)S(\theta)C(\phi) - C(\psi)S(\phi)) + F^I_{m,q_y} \tag{5}$$

$$m\ddot{Z} = -mg + TC(\theta)C(\phi) + F^I_{m,q_z} \tag{6}$$

$$I_x\ddot{\phi} = \dot{\theta}\dot{\phi}(I_y - I_z) - I_r\dot{\theta}\overline{\Omega} + T_{a_1} + M^B_{m,q_\phi} \tag{7}$$

$$I_y\ddot{\theta} = \dot{\psi}\dot{\phi}(I_z - I_x) + I_r\dot{\phi}\overline{\Omega} + T_{a_2} + M^B_{m,q_\theta} \tag{8}$$

$$I_z\ddot{\psi} = \dot{\theta}\dot{\phi}(I_x - I_y) + T_{a_3} + M^B_{m,q_\psi} \tag{9}$$

where F^I_{m,q_x}, F^I_{m,q_y}, and F^I_{m,q_z} are the interaction forces from the manipulator to the quadrotor in X, Y, and Z directions defined in the inertial frame and M^B_{m,q_ϕ} , M^B_{m,q_θ} , and M^B_{m,q_ψ} are the interaction moments from the manipulator to the quadrotor around X, Y, and Z directions defined in the inertial frame.

The variables in (4-9) are defined as follows: m is the mass of the quadrotor. T is the total thrust applied to the quadrotor from all four rotors, and is given by:

$$T = \sum_{i=1}^{4}(F_j) = \sum_{i=1}^{4}(K_F\Omega_j^2) \tag{10}$$

where F_j is the thrust force from rotor j, Ω_j is the angular velocity of rotor j and K_F is the thrust coefficient. T_{a_1}, T_{a_2}, and T_{a_3} are the three input moments about the three body axes, and are given as:

$$T_{a_1} = d(F_4 - F_2) \tag{11}$$

$$T_{a_2} = d(F_3 - F_1) \tag{12}$$

$$T_{a_3} = K_M(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \tag{13}$$

d is the distance between the quadrotor center of mass and the rotation axis of the propeller and K_M is the drag coefficient.

$$\overline{\Omega} = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4 \tag{14}$$

I_r is the rotor inertia. I_f is the inertia matrix of the vehicle around its body-frame assuming that the vehicle is symmetric about x-, y- and z-axis.

TABLE I
SYSTEM PARAMETERS

Par.	Value	Unit	Par.	Value	Unit
m	1	kg	L_2	$85x10^{-3}$	m
d	$223.5X10^{-3}$	m	m_0	$30x10^{-3}$	kg
I_x	$13.215X10^{-3}$	$N.m.s^2$	m_1	$55x10^{-3}$	kg
I_y	$12.522X10^{-3}$	$N.m.s^2$	m_2	$112x10^{-3}$	kg
I_z	$23.527X10^{-3}$	$N.m.s^2$	I_r	$33.216X10^{-6}$	$N.m.s^2$
L_0	$30x10^{-3}$	m	L_1	$70x10^{-3}$	m
K_{F_1}	$1.667x10^{-5}$	$kg.m.rad^2$	K_{F_2}	$1.285x10^{-5}$	$kg.m.rad^2$
K_{F_3}	$1.711x10^{-5}$	$kg.m.rad^2$	K_{F_4}	$1.556x10^{-5}$	$kg.m.rad^2$
K_{M_1}	$3.965x10^{-7}$	$kg.m^2.rad^2$	K_{M_2}	$2.847x10^{-7}$	$kg.m^2.rad^2$
K_{M_3}	$4.404x10^{-7}$	$kg.m^2.rad^2$	K_{M_4}	$3.170x10^{-7}$	$kg.m^2.rad^2$

B. System Parameters Estimation

In order to test the feasibility of the proposed system, a simulation framework will be built. Thus, there is a need to find the real parameters of the system to make the simulation results more accurate and reliable. The identified parameters include the structure parameters and rotor assembly (Electronic Speed Controller, Brush-less DC Motor, and Propeller) parameters (K_F and K_M). These parameters will be used in the system simulation and controller design later. A CAD model is developed using SOLIDWORKS to calculate the mass moments of inertia and all the missing geometrical parameters. We propose a methodology and implementation for the identification process in details in [20]. The identified parameters are given in Table I.

IV. CONTROLLER DESIGN

Quadrotor is an under-actuated system, because it has four inputs (angular velocities of its four rotors) and six variables to be controlled. By observing the operation of the quadrotor, one can find that the movement in x- direction is based on the pitch rotation, θ. Also the movement in y- direction is based on the roll rotation, ϕ. Therefore, motion along X- and Y-axes will be controlled through controlling θ and ϕ.

Fig. 3 presents a block diagram of the proposed control system. The control design criteria are achieving system stability and a zero trajectory tracking error under the effect of:

- Picking and placing a payload.
- Changing the operating region of the system.

The matrix G of the control mixer is used to transform the assigned thrust force and moments of the quadrotor (the control signals) from the controller block into assigned angular velocities of the four rotors. This matrix can be derived from (10-13) as in [12].

A. Robust Internal-loop Compensator Based Control

Disturbance-observer (DOB)-based controller design is one of the most popular methods in the field of motion control. In [21], the (DOB)-based controller is designed to realize a nominal system which can control acceleration in order to realize fast and precise servo system, even if servo system has parameter variation and suffers from disturbance. In [22], the generalized disturbance compensation framework, named the robust internal-loop compensator (RIC) is introduced and an advanced design method of a DOB is proposed based on the RIC. In [23], a control scheme based on RIC compensator for a clutch positioning system is proposed. The purpose of control is to achieve a precise position control of automotive dry-clutch actuator system module. A set of dynamic model is developed and validated experimentally. Robust internal-loop compensator is used to compensate unmodeled effect and unknown nonlinearities. In [24], the developed quadrotor shows stable flying performances under the adoption of RIC based disturbance compensation. Although a model is incorrect, RIC method can design a controller by regarding the inaccurate part of the model and sensor noises as disturbances.

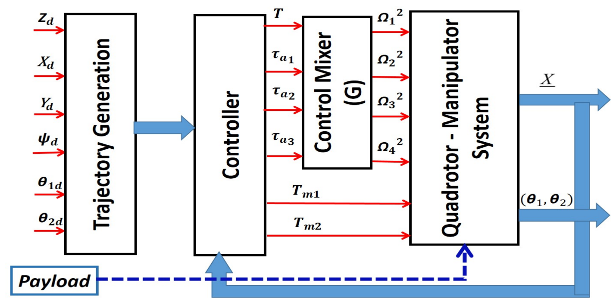

Fig. 3. Block Diagram of the Control System

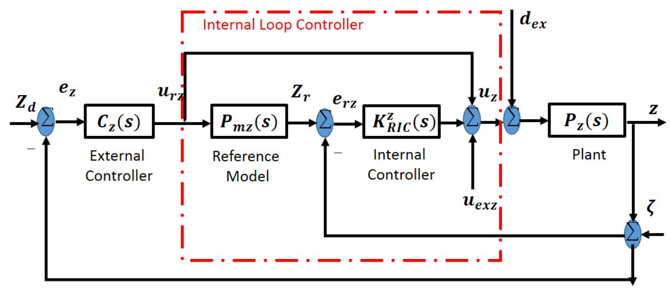

Fig. 4. RIC Disturbance Compensation Controller

We propose a robust internal loop compensator based control as robust controller to get accurate positioning of the proposed system. The controller consists of two parts, internal and external loop. Internal loop is used as a compensator for canceling disturbances, uncertainties and nonlinearities including difference between reference model and real system, while the external loop is designed to meet the specification of the system using the result of internal loop compensator.

The RIC based control algorithm, as shown in Fig. 4, controls the response of the plant $P(s)$ to follow that of the model plant $P_m(s)$ even though disturbances d_{ex} and sensor noise ζ are applied to the plant [22], [24], [25]. RIC based disturbance compensator can be used for position, attitude, and manipulator's joints control in the same way. For all controllers, the reference plant model are given in the form of:

$$P_{mi}(s) = \frac{1}{\tau_{c_i} s^2} \tag{15}$$

where $y_m(s)$ is the output response of the reference model (nominal plant), and $y_r(s)$ is the desired value of the plant. The value τ_i ($i = x$, y, z, ϕ, θ, ψ, θ_1, and θ_2), which depends on the plant dynamics, is mass for x, y, z-controller and mass moment of inertia for ϕ, θ, ψ, θ_1, and θ_2 .

The external-loop compensator $C_z(s)$ for altitude (z) control, for instance, are given like PD controller as follows:

$$C_z(s) = k_{pz} + k_{dz} s \tag{16}$$

with the error e_z = z_r - z as the controller input. where k_{pz} and k_{dz} are P- and D-gain of the external-loop compensator, respectively. The output of the external-loop compensator, i.e. the reference input of RIC, is given as

$$u_{rz}(s) = C_z(s) e_z \tag{17}$$

The output of the reference model is compared to the actual response generating the reference error e_{rz} = z_r - z which is applied to internal controller $K^z_{RIC}(s)$ that is chosen to be a PID-like controller and it is given as follows:

$$K^z_{RIC}(s) = k^z_p + k^z_d s + k^z_i \frac{1}{s} \tag{18}$$

Thus, the final control signal u_z is given as:

$$u_z = u_{cz} + u_{kz} + u_{exz} \tag{19}$$

where u_{cz} and u_{kz} are the control signals from the external and internal controllers respectively, while u_{exz} is an external value equal to the robot weight to compensate system weight (mg). The procedures for obtaining the RIC control input for X, Y, ϕ, θ, ψ, θ_1, and θ_2 control are the same with that for altitude (Z) control except that u_{exi} equal 0. In addition, there is difference in the design of X and Y controllers. In this control strategy, the desired pitch and roll angles, θ_d and ϕ_d , are not explicitly provided to the controller. Instead, they are continuously calculated by X and Y controllers in such a way that they stabilize the quadrotor's attitude. However, there is a need to convert the error and its rate of X and Y that is defined in the inertial frame into their corresponding values defined in the body frame. This conversion is done using the transformation matrix, defined in (1), assuming small angles approximation for ϕ and θ.

V. Simulation Results

Quintic Polynomial trajectories [18] are used as the reference trajectories for X, Y, Z, ψ, θ_1, and θ_2. Those types of trajectories have sinusoidal acceleration which is better in order to avoid vibrational modes. All trajectories have the same characteristics, the initial and final velocities and accelerations equal to zero, and the final time is 10 s and the simulation time is 70 s.

The system equations of motion and the control laws for both FMRLC and RIC techniques are simulated using MATLAB/SIMULINK program. The design details, simulation results, and parameters of FMRLC can be found in [13]. The controller parameters of the RIC controller are given in Table II. Those parameters are tuned to get the required system performance. The two controllers are tested to stabilize and track the desired trajectories under the effect of picking a payload of value 150 g at instant 15 s and placing it at instant 65 s. The simulation results of both FMRLC and RIC are presented in Fig. 5. These results show that RIC and FMRLC are able to track the desired trajectories (with different operating regions) before, during picking, holding, and placing the payload, in addition to, the RIC results are better than the FMRLC in disturbance rejection capability. Furthermore, the generated desired trajectories of θ and ϕ from RIC are smooth compared with that from FMRLC which are more oscillatory (see Fig. 5g and Fig. 5h). Moreover, since the RIC is simpler than FMRLC, the computation time for control laws of RIC is very small compared to that of FMRLC. Therefore, RIC is recommended to be implemented in experimental work.

TABLE II
RIC Parameters

$Par./Val.$	X	Y	Z	ϕ	θ	ψ	θ_1	θ_2
k_{pi}	0.3	0.3	5	30	30	5	5	5
k_{di}	0.7	0.7	3	5	5	3	3	3
k^i_p	0.001	0.001	5	30	30	5	5	5
k^i_d	0.001	0.001	3	5	5	3	3	3
k^i_i	0	0	1	10	10	1	1	1
τ_{ci}	1	1	1	0.01	0.01	0.02	0.1	0.1

VI. Conclusion

A new aerial manipulation robot called "Quadrotor Manipulation System", which provides solutions to the limitations found in the current aerial manipulation systems, was briefly described. Modeling, identification, and control of the proposed robot are discussed. RIC based control design is presented to stabilize the proposed system and is compared to the FMRLC. These controllers are tested to provide system stability and trajectory tracking under the effect of picking and placing a payload and the effect of changing the operating region. The system equations of motion are simulated using MATLAB/SIMULINK. Simulation results show that the two controllers have a close superior performance. However, the RIC based control has higher disturbance rejection abilities, is very simple, and has low computation time comparing with FMRLC. In addition, these results indicate the feasibility of the proposed system. Therefore, the RIC is highly recommended to be implemented in real time to experimentally control the proposed system.

Acknowledgment

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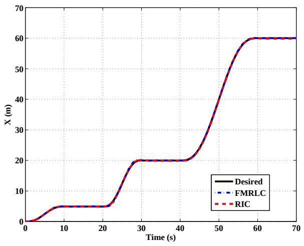
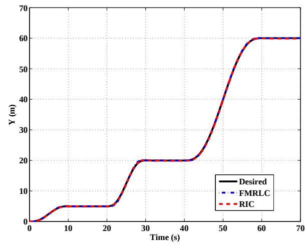
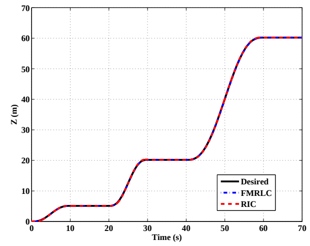


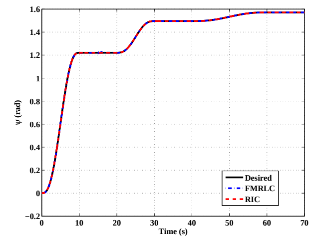
(a) X Response



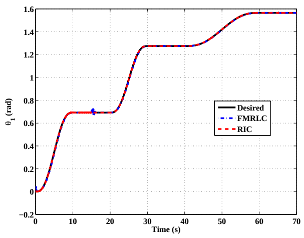
(b) Y Response



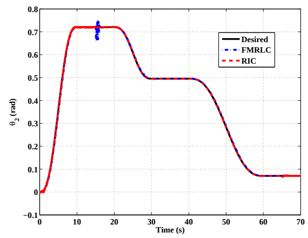
(c) Z Response



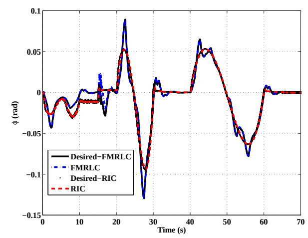
(d) ψ Response



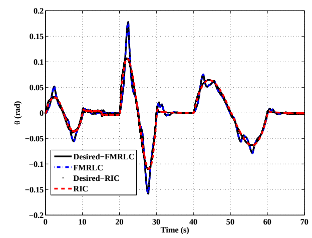
(e) θ_1 Response



(f) θ_2 Response



(g) ϕ Response



(h) θ Response

Fig. 5. The Actual Response of both RIC and FMRLC Techniques: a) X, b) Y, c) Z, d) ψ, e) θ_1, f) θ_2, g) ϕ, and h) θ.

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